Impact of Aeration on Maize Weevil (Coleoptera: Curculionidae) Populations in Corn Stored in the Northern United States: Simulation Studies

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ABSTRACT Historical weather data were used to divide the northern United States into five climatic zones based on the number of hours below 15.6°C (60°F), which is the approximate lower developmental threshold for the maize weevil, *Sitophilus zeamais* Motschulsky, during a calendar year. A model for population growth and development of the maize weevil, which is integrated with a bin-cooling model, was used to predict temperature, relative humidity, number of larvae, and number of adults in unaerated and aerated corn during 1 yr of storage. In all zones, predicted temperature profiles in unaerated corn indicate that it would take 2-3 mo for grain temperatures to reach the developmental threshold of 15.6°C, whereas aeration would rapidly lower grain temperatures to this temperature. In unaerated and aerated corn, predicted relative humidity would gradually decline with temperature. Larval populations in unaerated corn were predicted to increase during autumn, although numbers would decrease as the climatic zones progressed northward. In all zones, the predicted number of larvae in unaerated corn would decline through winter and spring of the following year because temperatures would be well below the developmental threshold of 15.6°C, and it would increase beginning in midsummer when temperatures increase. Except for corn stored in the southernmost zone, adult populations were not predicted to increase during autumn in unaerated corn because temperatures would not be warm enough to complete a generation. However, predicted adult populations in unaerated corn stored in all zones would begin to increase in August and September of the following year when larvae already present in the kernels complete development. Predicted populations of larvae in aerated corn stored in all but the southernmost zones would decline during autumn because of the rapid cooling provided by aeration, and in each zone the total number at the end of the calendar year would be about two orders of magnitude lower than in unaerated corn. Aeration would reduce the number of adults to about 1.5-2.0 orders of magnitude less than the numbers predicted for unaerated corn. Advancing the storage date by 1 or 2 wk would have little effect on predicted populations of larvae or adults in unaerated or aerated corn stored in the three northernmost zones. Results of these simulation studies show that aeration alone without the use of insecticides should provide adequate management of maize weevil in corn stored in the northern United States.

Corn (*Zea mays* L.) is an important field crop in many areas of the United States east of the Rocky Mountains. Harvest can occur from mid-August in the Deep South to early November along the Canadian border, with minor variations caused by specific growing conditions. After harvest, corn is stored on-farm or in commercial elevators, and it can be infested by a variety of stored-product insects (Arbogast and Mullen 1988, Arbogast and Throne 1997). One of the major pests is the maize weevil, *Sitophilus zeamais* Motschulsky, an internal feeder. Females oviposit directly into the kernel; the larva develops inside the kernel and pupates; and the adult bores out of the kernel. The lower limit of development for the maize weevil is approximately 15°C, with optimum population growth occurring at approximately 28°C (Throne 1994). The maize weevil is a more serious pest in warmer areas because environmental conditions are suitable for population growth for longer periods of time as corn harvest and storage occur earlier in the year. Once infestations become established in stored corn, fumigation with phosphine may be necessary to prevent economic damage.

Aeration is an important component of management practices for other stored commodities, including hard red winter wheat (*Triticum aestivum* L.) harvested and stored in the central plains. Several recent field trials (Reed and Harner 1997) and simulation studies (Flinn et al. 1997) have documented the benefits of using automatic aeration controllers to cool wheat in distinct cycles below specified temperature thresholds rather than using manual aeration or continual aeration for specified time periods without set thresholds. Published reports also have demonstrated the benefits of aeration for stored corn. In small-scale field studies, continual aeration during autumn reduced insect populations and slowed the degradation rate of pirimiphos-methyl in corn stored in Georgia (Arthur 1994, Arthur and Throne 1994). Maier et al. (1996) conducted simulation studies and evaluated several management strategies for corn stored in Indianapolis, IN; Columbia, SC; and Amarillo, TX; and showed that continual autumn aeration to levels of 5-12.5°C reduced maize weevil population levels well below those in unaerated corn. However, timed and controlled aeration was not investigated as part of the study.

The only published simulation study predicting the effects of controlled aeration on temperatures and maize weevil populations in stored corn is by Arthur et al. (1998). Historical weather data were used to divide the southern United States into five climatic zones, estimate periods in which controlled aeration cycles could be completed for corn stored in each zone using nine temperature-airflow rate combinations, and predict maize weevil population development in unaerated versus aerated corn. Activation temperatures were 18.3, 15.6, and 12.8°C (65, 60, and 55°F, respectively), and airflow rates were 0.0013, 0.0026, and 0.0039 $m^3/s/m^3$ (0.1, 0.2, and 0.3ft^3/min/bushel, or cubic feet/minute [CFM]/bushel, respectively). The combination that produced the lowest predicted maize weevil populations was 15.6°C and 0.0013$m^3/s/m^3$. Aeration at the two higher rates did not yield the expected decrease in predicted maize weevil populations. In all zones, predicted population levels in aerated corn were much lower than in unaerated corn. Results also indicated that fumigation treatments might have to be combined with aeration in the Deep South to manage maize weevils in stored corn.

Most of the corn in the United States is grown in the northern part of the country, where temperatures at harvest are much cooler compared with the southern part. Aeration alone may limit maize weevil populations without the need for insecticides. The objectives of this study were as follows: (1) to use historical weather data to partition the northern United States into climatic zones; (2) to predict the population levels and developmental patterns of maize weevils in unaerated and aerated corn in 1 yr, starting with the binning date in one year and ending with the day before that date the next year (*storage year*), for corn stored in the locations represented by the weather stations within each zone; and (3) to determine the effect of either delaying or advancing the binning dates for individual stations selected to represent each zone, thus simulating variation in harvest times (early versus later harvest).

Materials and Methods

The northern United States was defined as states north of Oklahoma, Arkansas, Tennessee, and North Carolina and east of Montana, Wyoming, and Colorado (Fig. 1). Weather data (in °F) from the National Climatic Data Center in Asheville, NC (Samson CD-Rom), were used to identify the primary airport weather stations within each state. Data for each of these locations (87 total sites) then were obtained from weather compact disks available from Earth Info (Boulder, CO, also in °F) for the years 1960 to 1989. The daily maximum and minimum temperatures on each date for each of the 30 yr were averaged using the means procedure (SAS Institute 1987) to obtain the average maximum and minimum temperatures on that date during the 30-yr cycle from 1960 to 1989. This same summarization procedure was used in several recent simulation studies where the intent was to describe broad geographic patterns for different regions of the United States (Arthur et al. 1998, Arthur and Flinn 2000). Daily sunrise and sunset at each station were obtained using a formula obtained from the U.S. Department of Energy (SOLMET 1979). Hourly temperatures then were estimated from daily mean minimum and maximum temperatures and the sunrise and sunset using a QBASIC model previously described in detail (Arthur and Johnson 1995). Yearly hours of temperature accumulation below 15.6°C then were calculated for each site, similar to methods used for other simulation studies using this same QBASIC program.

The total number of hours below 15.6°C during the calendar year ranged from 4,548 in Norfolk, VA, to 7,342 in Sault Ste. Marie, MI (Table 1). Five climatic zones were approximated by using Surfer (Golden Software 1994a) and Map Viewer software (Golden Software 1994b) to draw contour lines based on total hours of temperature accumulations below 15.6°C in 1 yr as follows: zone 1, <5,000 h; zone 2, 5,000-5,600 h; zone 3, 5,600-6,200 h; zone 4, 6,200-6,800 h; and, zone 5, >6,800 h (Fig. 1). The average dates that corn would be stored and binned in zones 1-5 were estimated as 1, 8, 15, 22, and 29 October, respectively, based on data from summary reports on corn harvest produced by statistical reporting services in individual states.

Maize weevil population growth was simulated for each station by integrating a model for maize weevil population development, described in detail by Throne (1994), with a bin-cooling model based on equations described by Parry (1985). The meteorological data for each station was obtained from the Samson weather compact disk, which contains hourly data for 21 different parameters. Input parameters used for the simulation model were maximum and minimum temperature, relative humidity, extraterrestrial direct normal radiation, global horizontal radiation, wind speed, and snow cover, and these parameters were summarized by averaging the daily hourly values for each parameter on each day for each year from 1960 to 1989 to create a data set with average hourly values for the 30-yr

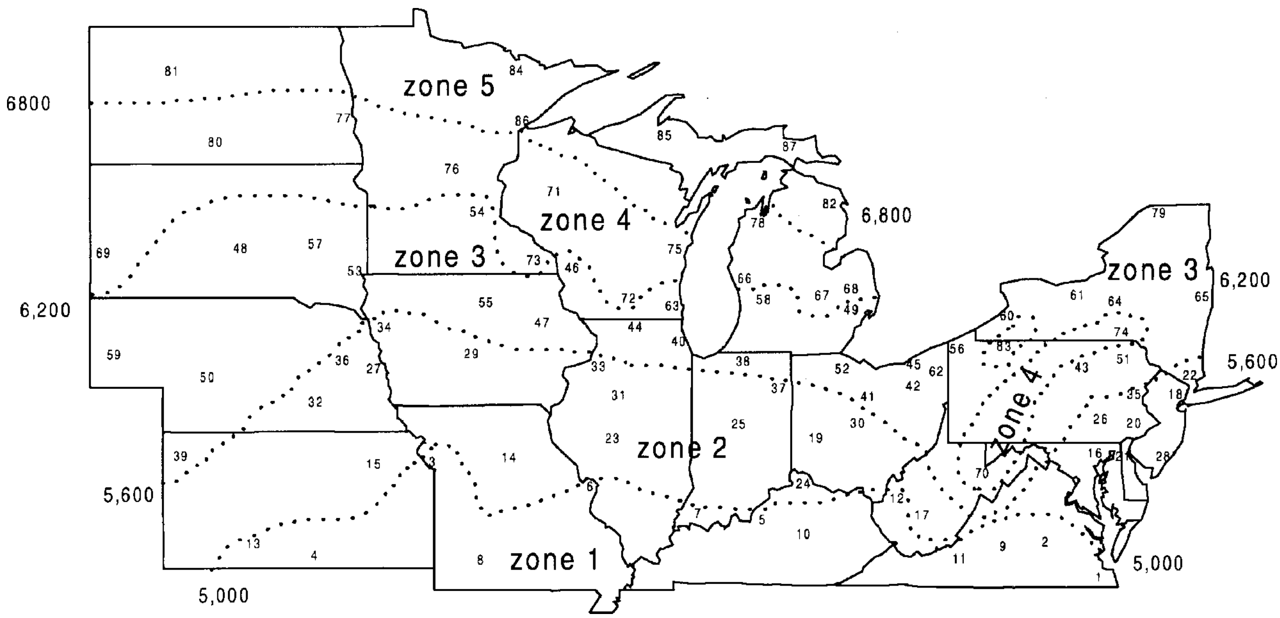

Fig. 1. Approximate location of weather stations (indicated by small numbers corresponding to ID Nos. in Table 1) and delineation of climatic zones for corn stored in northern United States, based on yearly number of hours below 15.6°C. Zone 1, <5,000 h; zone 2, 5,000 — 5,600 h; zone 3, 5,600 — 6,200 h; zone 4, 6200 — 6800 h; and, zone 5, >6,800 h.

Table 1. Location of weather stations and estimated mean number of hours per year below 15.6 °C at each station based on average daily maximum and minimum temperatures from 1960 to 1989

ID NO	Location	Hours below 15.6°C	ID NO	Location	Hours below 15.6°C
1	Norfolk, VA	4,548	45	Cleveland, OH	5,840
2	Richmond, VA	4,781	46	La Crosse, WI	5,869
3	Kansas City, MO	4,819	47	Waterloo, IA	5,894
4	Wichita, KS	4,913	48	Pierre, SD	5,919
5	Louisville, KY	4,922	49	Detroit, MI	5,944
6	St. Louis, MO	4,941	50	North Platte, NE	5,945
7	Evansville, IN	4,974	51	Wilkes Barre, PA	5,945
8	Springfield, MO	5,000	52	Toledo, OH	5,957
9	Lynchburg, VA	5,016	53	Sioux Falls, SD	5,962
10	Lexington, KY	5,066	54	Minneapolis, MN	5,999
11	Roanoke, VA	5,069	55	Mason City, IA	6,015
12	Huntington, WV	5,088	56	Erie, PA	6,066
13	Dodge City, KS	5,104	57	Huron, SD	6,084
14	Columbia, MO	5,111	58	Grand Rapids, MI	6,095
15	Topeka, KS	5,121	59	Scottsbluff, NE	6,106
16	Baltimore, MD	5,127	60	Buffalo, NY	6,124
17	Charleston, WV	5,164	61	Rochester, NY	6,124
18	Newark, NJ	5,171	62	Youngstown, OH	6,184
19	Dayton, OH	5,183	63	Milwaukee, WI	6,189
20	Philadelphia, PA	5,184	64	Syracuse, NY	6,206
21	Wilmington, DE	5,207	65	Albany, NY	6,223
22	New York City, NY	5,236	66	Muskegon, MI	6,230
23	Springfield, IL	5,247	67	Lansing, MI	6,262
24	Covington, KY	5,255	68	Flint, MI	6,265
25	Indianapolis, IN	5,332	69	Rapid City, SD	6,316
26	Harrisburg, PA	5,366	70	Elkins, WV	6,320
27	Omaha, NE	5,405	71	Eau Claire, WI	6,326
28	Atlantic City, NJ	5,442	72	Madison, WI	6,326
29.	Des Moines, IA	5,462	73	Rochester, MN	6,328
30	Columbus, OH	5,505	74	Binghamton, NY	6,453
31	Peoria, IL	5,505	75	Green Bay, WI	6,528
32	Grand Island, NE	5,528	76	Saint Cloud, MN	6,528
33	Moline, IL	5,545	77	Fargo, ND	6,538
34	Sioux City, IA	5,560	78	Traverse City, MI	6,659
35	Allentown, PA	5,617	79	Massena, NY	6,667
36	Norfolk, NE	5,632	80	Bismarck, ND	6,671
37	Fort Wayne, IN	5,654	81	Minot, ND	6,692
38	South Bend, IN	5,698	82	Alpena, MI	7,033
39	Goodland, KS	5,740	83	Bradford, PA	7,100
40	Chicago, IL	5,766	84	Internat. Falls, MN	7,162
41	Mansfield, OH	5,801	85	Houghton, MI	7,238
42	Akron, OH	5,816	86	Duluth, MN	7,273
43	Williamsport, PA	5,821	87	Sault Ste. Marie, MI	7,342
44	Rockford, IL	5,825			

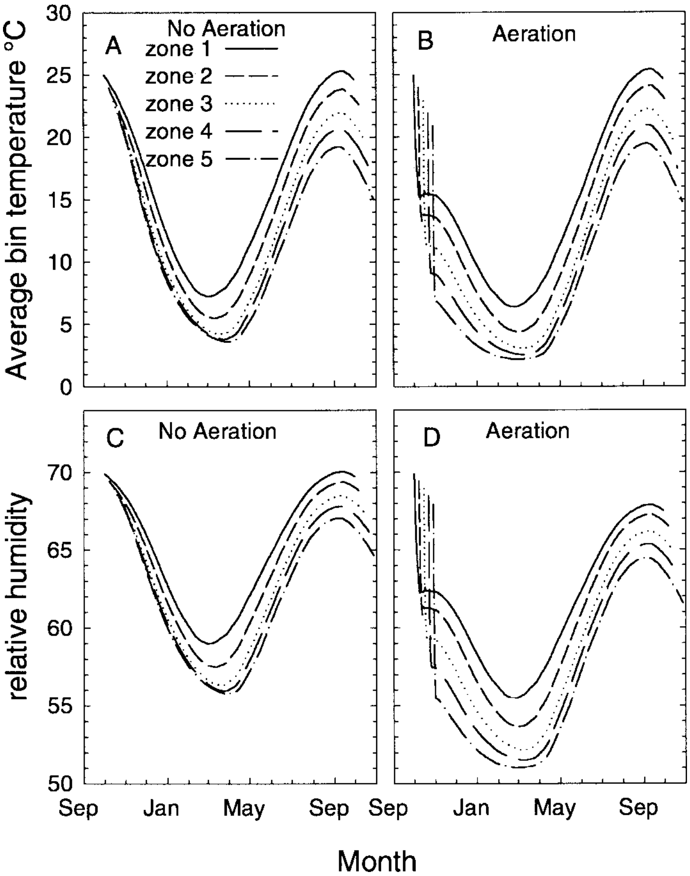

Fig. 2. Predicted average temperatures and relative humidities in unaerated and aerated corn stored in five climatic zones within the northern United States. A and B, predicted grain temperatures in unaerated and aerated corn, respectively. C and D, predicted relative humidities in unaerated and aerated corn, respectively.

period. This data set was copied to create a 2-yr data set used to run the model simulations. This average weather data set created from the Samson compact disk file was used as the input weather data set, following procedures used in the previous simulation study for corn stored in the southern United States (Arthur et al. 1998). In that study, the southern United States was divided into five zones, storage capacity was constant at 76,376 kg (3,000 bushels), and starting grain temperatures were 30-26°C as the zones progressed northward. Therefore, in this study for the northern United States storage capacity was the same, and starting grain temperatures were 25 to 21°C for zones 1-5, respectively, to correspond to later harvest dates as the zones progressed northward. Simulations were run using the average 30-yr weather data set for each location to predict the number of larvae and adult weevils produced in 1 yr in unaerated corn, assuming that 10 males and 10 females entered the bin on the binning date. Yearly simulations were run in the same manner for aerated storage except that the aeration subroutine was activated to cool the corn at the airflow rate of $0.0013 m^3/s/m^3$ whenever ambient temperatures fell below 15.6°C and until 120 h of aeration were accumulated. This value of 120 h was used because it is the theoretical time required to move a cooling front through a grain mass at an airflow rate of $0.0013 m^3/s/m^3$ (Arthur and Johnson 1995).

The simulation results for each station within a zone were averaged and plotted to compare predicted grain temperature and relative humidity and predicted larval and adult populations of maize weevil in unaerated versus aerated corn. Within each zone, one station was selected to represent that zone, based on the median population of adults in the simulations for unaerated corn for all stations within that zone. Additional simulations were run for that one station in each zone by delaying or advancing the binning date by 1 or 2 wk to simulate an earlier or later corn harvest and binning date. The stations selected were: zone 1, Springfield, MO; zone 2, Indianapolis, IN; zone 3, Scotts Bluff, NE; zone 4, Madison, WI; and zone 5, International Falls, MN.

Results

The results of the simulations show that predicted temperatures in unaerated corn stored in each zone would gradually decline during the fall and winter to minimum levels of approximately 4-8°C in March of the following year, and then would increase during the summer to levels ranging from about 19°C in zone 5 to almost 26°C in zone 1 (Fig. 2A). In contrast, the predicted temperatures for aerated corn stored in each zone would drop rapidly by approximately 10°C from the starting grain temperatures (25, 24, 23, 22, and 21°C in zones 1-5, respectively) (as shown by the vertical lines in Fig. 2B). However, the predicted minimum temperatures, patterns of increased temperature during the summer, and maximum temperatures attained were similar in aerated and unaerated corn. Predictions for relative humidity in unaerated corn stored in each zone show a gradual decline from 70 to 56-59%, followed by an increase to levels ranging from 67% in zone 5 to 70% in zone 1 (Fig. 2C). Predicted relative humidity in aerated corn immediately dropped 7-10% in each zone, and predicted minimum values were lower than those in unaerated corn (Fig. 2D). Relative humidity in both unaerated and aerated corn decreased and increased along with temperature, although the predicted maximum relative humidity attained during the summer was slightly lower in aerated corn than in unaerated corn.

Model simulations show that the predicted number of larvae per bushel in unaerated corn stored in zones 1-4 increase rapidly during October to December, then decline gradually through the spring and early summer (Fig. 3A). Populations in these same zones were predicted to increase exponentially in late July to mid-September, occurring later in succession with each zone. The predicted number of larvae present at the end of the storage year was lower as the zones progressed northward. At the conclusion of the 1-yr storage period (9/30, 10/7, 10/14, 10/21 for zones 1-4, respectively), populations of larvae ranged from <1 per bushel for corn stored in zone 4 to approximately 100 per bushel for corn stored in zone 1. Larval populations in corn stored in zone 5 were predicted to increase slightly during the fall, gradually decline during the winter, and die out during the summer.

Predicted densities of larvae in aerated corn stored in zones 1-3 followed the same patterns of decline and increase as populations in unaerated corn, but maximum values for immature weevils in aerated corn at the end of the storage year were lower compared with unaerated corn (Fig. 3B). Predicted levels for larvae in aerated corn stored in zones 1-3 did not exceed two larvae per bushel, and no larvae were predicted in aerated corn stored in zones 4 and 5.

The predicted number of adults in unaerated corn stored in zone 1 increased from the starting values of 6.7×10^{-3} (20 adults/3,000 bushel-bin) in late fall, remained stable from January to mid-August, and then increased exponentially starting in early September (Fig. 3C). The number of adults at the end of the storage year was approximately 10 per bushel. Adults stored in zone 2 increased slightly during the fall, remained at that level until July, and then increased to maximum levels of approximately 2/bushel. The predicted number of adults in unaerated corn stored in zone 3 decreased during fall and winter when no larvae were completing development to the adult stage, and adult populations did not increase until July or August of the following year. Although the number of

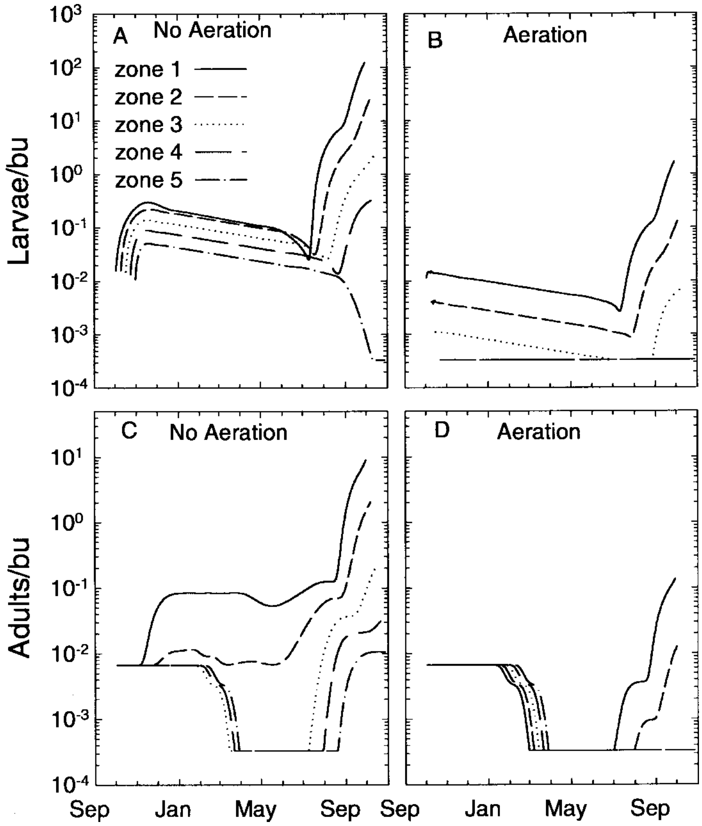

Fig. 3. Predicted numbers of larvae and adult weevils per bushel after 1 yr in unaerated and aerated corn stored in five climatic zones within the northern United States. Simulations were run assuming 10 males and 10 females entered bin on the date corn was stored. A and B, predicted larval populations in unaerated and aerated corn, respectively. C and D, predicted adult populations in unaerated and aerated corn, respectively.

adults in unaerated corn stored in zones 4 and 5 began a period of exponential increase in late August-early September, maximum levels at the end of the year were approximately 0.015 to 0.020/bushel in the two zones (Fig. 3C). The predicted number of adults in aerated corn stored in zones 1 and 2 declined during the winter and spring of the following year, then slightly increased beyond the starting values during August and September (Fig. 3D). The predicted number of adults at the conclusion of the storage period in zones 1 and 2 were much lower than the number in unaerated corn stored in the same zones (Fig. 3D). No adults were predicted for aerated corn stored in zones 3-5.

In Springfield, MO, larval and adult populations were predicted to increase in unaerated corn and decrease in aerated corn with each successive binning date (Table 2). The predicted increases with the later binning date reflect the fact that temperatures in September were warm; and when simulations were run for the entire year, exponential growth occurred in September of the second year. Similar trends occurred for immature and adult populations in unaerated and aerated corn stored in Indianapolis, IN; and in Scotts Bluff, NE. Advancing or delaying the binning date had minimal effect on immature and adult populations in either unaerated or aerated corn stored in Madison, WI. Predicted levels of larval and adult populations in International Falls, MN, did not exceed 0.01/bushel in any simulations.

Discussion

Simulations were run assuming 10 males and 10 females entered the bin on the date corn was loaded into storage. However, the predicted patterns of maize weevil population development would remain the same regardless of the number of starting adults. Increasing the numbers of each sex from 10 to 100 simply shifts all of the predicted population curves one order of magnitude. In all of the climatic zones chosen to represent the northern United States, aeration dramatically reduced populations of both larvae and adults. In unaerated corn, larval populations would increase in autumn; whereas in aerated corn, larval populations would decline rapidly during autumn. When large numbers of weevils were present during autumn in unaerated corn, predicted populations of larvae and adults would increase in late summer of the following year. Within each climatic zone, the predicted numbers of larvae and adults at the end of the year were at least two orders of magnitude lower in aerated versus unaerated corn.

The rice weevil, *Sitophilus oryzae* (L.), is a cold-tolerant species relative to other stored-product beetles and can complete development from egg to adult at temperatures as low as 17°C (Howe 1965, Fields 1992). Some published studies indicate that the maize weevil may be even more cold-tolerant than the rice weevil. Nakakita and Ikenaga (1997) reported that rice weevils did not develop at 15°C, whereas few maize weevils were able to emerge as adults when reared at that temperature. Throne (1994) reported 27% survivorship from egg to adult of maize weevils reared at 15°C. Our simulations showed that predicted temperatures in unaerated corn would not drop to 15°C until December and would remain below this threshold until summer (about 6-8 mo), depending on the climatic zone. Autumn aeration would quicky lower the temperatures in aerated corn to 15.6°C or less and although temperatures in unaerated and aerated corn would start to increase at about the same time the following summer, the temperature in aerated corn would be below 15.6°C for about 8 or 10 mo. This extended period below 15.6°C obviously limits maize weevil population growth more in aerated than in unaerated corn.

Cooling may also reduce maize weevil oviposition. In the study by Nakakita and Ikenaga (1997), oviposition and metamorphosis of maize weevil was inhibited completely at 10°C. Throne (1994) reported that although the maize weevil oviposited and both eggs and larvae of the maize weevil could survive at 10°C, none survived to the adult stage. In unaerated corn, the times in which temperatures were below 10°C in the warmest zone (1) and the coolest zone (5) were approximately 4 and 5 mo, respectively; in aerated corn, temperatures were below 10°C for approximately 4 mo in zone 1 and 7 mo in zone 5.

When maize weevils develop to the adult stage, they bore an exit hole in the kernel. These kernels can be identified as insect-damaged kernels, and the presence of insect-damaged kernels provides an estimate of the quality of the corn. Except for the southernmost zone 1, unaerated corn could be stored for 8 or 10 mo in most of the northern United States before adults would begin to emerge from kernels. However, even though a generation could not be completed in the fall, oviposition and larval development could increase for several months until ambient cooling limits population growth. The presence of larvae within the kernel can have an effect on quality. Barney et al. (1991) reported an increase in the percentage of ash, lipids, and proteins and a decrease in kernel weights when corn was infested with maize weevils. Adams (1976) also reported a weight loss in kernels when maize weevils were reared from eggs to adults at 27°C. Dead larvae in the kernels and dead adults can result in insect fragment counts in the final product. Reducing the fall population of larvae through aeration could improve the quality of stored corn, even if that corn were removed from storage before these larvae develop to the adult stage.

When developing predictions for field crop insects, extreme weather conditions would be important because these insects

Table 2. Predicted number of maize weevil larvae and adults (per bushel) produced in calendar year from introduction of 10 males and 10 females in unaerated and aerated corn stored in northern United States on five binning dates

Station	Binning Date	Larvae		Adults	
		Unaerated	Aerated	Unaerated	Aerated
Springfield,	9/17	69.28	4.27	8.30	0.53
MO (zone 1)	9/24	97.85	3.10	7.94	0.29
	10/1	128.01	1.08	7.96	0.09
	10/8	148.33	1.09	9.69	0.08
	10/15	169.91	1.18	14.36	0.08
Indianapolis,	9/24	7.64	0.26	1.35	0.05
IN (zone 2)	10/1	11.52	0.13	1.72	0.02
	10/8	17.74	0.08	1.91	0.01
	10/15	25.03	0.13	2.02	0.02
	10/22	32.53	0.08	2.11	<0.01
Scotts Bluff,	10/1	2.61	0.01	0.26	<0.01
NE (zone 3)	10/8	2.99	<0.01	0.45	<0.01
	10/15	4.02	<0.01	0.60	<0.01
	10/22	4.67	<0.01	0.70	<0.01
	10/29	4.56	<0.01	0.74	<0.01
Madison,	10/8	0.65	<0.01	0.03	<0.01
WI (zone 4)	10/15	0.66	<0.01	0.03	<0.01
	10/22	0.63	<0.01	0.03	<0.01
	10/29	0.57	<0.01	0.02	<0.01
	11/5	0.50	<0.01	0.02	<0.01
International Falls,	10/15	<0.01	<0.01	<0.01	<0.01
MN (zone 5)	10/22	<0.01	<0.01	<0.01	<0.01
	10/29	<0.01	<0.01	<0.01	<0.01
	11/5	<0.01	<0.01	<0.01	<0.01
	11/12	<0.01	<0.01	<0.01	<0.01

[a] Zones defined in text and Fig. 1.

usually are subject to fluctuations in ambient temperature, and yearly variations could affect population development. Extreme weather years and patterns may have minimal impact on stored grain insects such as the maize weevil because they are insulated from temperature variations by the moderating effects of the bulk grain mass. Studies by Longstaff and Banks (1987) show that at a depth of 0.4 m or more, temperature will change slowly with daily variation in ambient temperatures. Kawamoto et al. (1991, 1992) described how selected meteorological data for several individual years and locations, or 30-40 yr of average data for a larger number of locations, can be used to predict the risk of insect infestations in stored raw commodities. Maier et al. (1996) conducted simulation studies comparing different aeration management strategies on temperature patterns and maize weevil development in stored corn based on individual yearly climatic data from 1961 to 1990 for Indianapolis, IN; Columbia, SC; and Amarillo TX. Similarly, Flinn et al. (1997) conducted simulation studies of development for the rusty grain beetle, *Cryptolestes ferrugineus* (Stephens), in wheat stored in Topeka, KS; Oklahoma City, OK; and Sioux City, SD; using yearly data from 1983 to 1987. We conducted our simulations by averaging 30 yr of daily temperature data for each of 87 weather stations to determine total hours of temperature below 15.6°C during the year and averaging 30 yr of hourly climatic data for each station to predict maize weevil population development. We used a large number of stations so that results would be applicable for a broad area, the northern United States.

Similar procedures were used to classify the southern United States into climatic regions to predict maize weevil development in stored corn (Arthur et al. 1998). Increasing the airflow rate from 0.0013 $m^3/s/m^3$ to 0.0026 and 0.0039 $m^3/s/m^3$ (0.1, 0.2, and 0.3 ft^3/min/bushel, or CFM, respectively) did not produce an expected decrease in predicted populations of adult maize weevils, and the optimum temperature for aeration was 15.6°C. Thus, the simulation studies for the northern United States were conducted using the single airflow rate of 0.0013 $m^3/s/m^3$ combined with an aeration activation temperature of 15.6°C. These modeling techniques also have been used to predict temperature accumulations and the impact of aeration on the rusty grain beetle in stored hard red winter wheat (Arthur and Flinn 2000).

The number of larvae and adults in both unaerated and aerated corn would be expected to decrease with the northward progression of the climatic zones. With the exception of the warmest areas, maize weevils may not be able to complete a generation during autumn in unaerated corn stored in the northern United States. In addition, advancing the storage date by 1 or 2 wk will have little effect on larval or adult populations in the coldest regions of the northern United States. In our previous simulation study for the southern United States, adults were predicted to increase continually during autumn in unaerated corn stored in the five climatic zones, and the total numbers at the end of the year from the introduction of 10 males and 10 females were far greater than the numbers obtained for the northern United States (Arthur et al. 1998). These simulation studies indicate that aeration alone would not be a viable management option to control maize weevils in corn stored in the Deep South because of the population growth and development that would occur before the corn could be cooled through aeration. The combination of earlier harvest and storage dates, warmer temperatures for the initial months of storage, and the time delays before aeration could be employed interact to create more of a potential for high numbers of maize weevils in corn stored in the southern versus the northern states. In the northern United States, it should be possible to manage maize weevils in stored corn without the need for insecticides.

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